New Light on Dark Matter from the LHC

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Abstract

The prospects for detecting a candidate supersymmetric dark matter particle at the LHC are reviewed, and compared with the prospects for direct and indirect searches for astrophysical dark matter, on the basis of a frequentist analysis of the preferred regions of the Minimal supersymmetric extension of the Standard Model with universal soft supersymmetry breaking (the CMSSM) and a model with equal but non-universal supersymmetry-breaking contributions to the Higgs masses (the NUHM1). LHC searches may have good chances to observe supersymmetry in the near future - and so may direct searches for astrophysical dark matter particles.

1   Introduction

There is a standard list of open questions beyond the Standard Model of particle physics [1], which includes the following. (1) What is the origin of particle masses and, in particular, are they due to a Higgs boson? (2) Why are there so many different types of standard matter particles, notably three neutrino species? (3) What is the dark matter in the Universe? (4) How can we unify the fundamental forces? (5) Last but certainly not least, how

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may we construct a quantum theory of gravity? Each of these questions will be addressed, in some way, by experiments at the LHC, though answers to all of them are not guaranteed!

The central topic of this talk is, of course, question (3) concerning dark matter. Certainly there are many candidate particles, ranging in mass from axions to Wimpzillas. However, many candidates fall within the general category of WIMPs (weakly-interacting massive particles) weighing between ~ 100 and ~ 1000 GeV and hence possibly accessible to the LHC. These include the lightest Kaluza-Klein particle (LKP) in some scenarios with extra dimensions [2], the lightest T-odd particle (LTP) in some little Higgs scenarios [3], and the lightest supersymmetric particle (LSP) in supersymmetric models in which R-parity is conserved [4].

Historically, the LSP was the first of these WIMP candidates, and personally I still find the LSP the best motivated, since there are so many reasons to favour supersymmetry at the TeV scale [1]. It would help the Higgs boson do its job [(1) above], by cancelling the quadratically-divergent contributions to its mass, and thereby stabilizing the electroweak mass scale [5]. Further, supersymmetry predicts the appearance of a Higgs boson at a mass ~ 130 GeV or below, as indicated by the precision electroweak data [6]. Supersymmetry at the TeV scale would also aid in the grand unification of the strong, weak and electromagnetic interactions [7] by enabling their strengths to evolve to a common value at some high-energy GUT scale [(4) above]. Moreover, supersymmetry is apparently essential in stringy attempts to construct a quantum theory of gravity [(5) above]. However, as Feynman surely would have said, you would not give five arguments for supersymmetry if you had one good argument, so let us focus on that: the LSP is an excellent candidate for dark matter [(3) above] [4], as we now discuss.

2 Supersymmetric Models

We work within the framework of the minimal supersymetric extension of the Standard Model (MSSM), in which the known particles are accompanied by simple supersymmetric partners and there are two Higgs doublets, with a superpotential coupling denoted by μ and a ratio of Higgs v.e.v.s denoted by $\tan \beta$ [8]. The bugbear of the MSSM is supersymmetry breaking, which occurs generically through scalar masses m_0, gaugino fermion masses $m_{1/2}$, trilinear soft scalar couplings A_0 and bilinear soft scalar couplings B_0. In our ignorance about them, the total number of parameters in the MSSM exceeds 100! For simplicity, it is often assumed that these parameters are universal

at the scale of grand unification, so that there are single soft supersymmetry-breaking parameters $m_0, m_{1/2}, A_0$, a scenario called the constrained MSSM (CMSSM) [1]. However, this assumption is not strongly motivated by either fundamental theory or phenomenology. Moreover, as discussed below, even if $m_0, m_{1/2}, A_0$ are universal, this may be true at some scale different from the GUT scale [10, 11].

What happens if the soft supersymmetry-breaking parameters are not universal? Upper limits on flavour-changing neutral interactions disfavour models in which different sfermions with the same internal quantum numbers, e.g., the $\tilde{d}, \tilde{s}$ squarks have different masses [12]. But what about squarks with different internal quantum numbers, or squarks and sleptons? Various GUT models impose some relations between them, e.g., the $\tilde{d}_R$ and $\tilde{e}_L$ scalar masses are universal in SU(5) GUTs, as are the $\tilde{d}_L, \tilde{u}_L, \tilde{u}_R$ and $\tilde{e}_R$ scalar masses, and all are equal in SO(10) GUTs. However, none of these arguments rules out non-universal supersymmetry-breaking scalar masses for the Higgs multiplets, so one may also consider such non-universal Higgs models (NUHM) with either one or two additional parameters (NUHM1, NUHM2). Who knows where string models may finish up among or beyond these possibilities?

The LSP is stable in many supersymmetric models because of a conserved quantity known as R parity, which may be expressed in terms of baryon number B, lepton number L and spin S as $R \equiv (-1)^{2S-L+3B}$. It is easy to check that all Standard Model particles have $R = +1$ and their supersymmetric partners have $R = -1$. The multiplicative conservation of R implies that sparticles must be produced in pairs that heavier sparticles must decay into lighter sparticles, and that the LSP is stable, because it has no legal decay mode. It should lie around in the Universe today, as a supersymmetric relic from the Big Bang [4].

In such a scenario, the LSP could have no strong or electromagnetic interactions [4], since otherwise it would bind to ordinary matter and be detectable in anomalous heavy nuclei, which have been looked for, but not seen. Possible weakly-interacting scandidates include *a priori* the sneutrinos - which have been excluded by LEP and by direct astrophysical searches for dark matter, the lightest neutralino χ - a mixture of the spartners of the Z, γ and neutral Higgs boson, and the gravitino - the supersymmetric partner

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[1]I emphasize that the CMSSM is not to be confused with minimal supergravity (mSUGRA), which imposes a specific relationship between the trilinear and bilinear couplings: $B_0 = A_0 - m_0$ as well as a relationship between the scalar and gravitino masses: $m_0 = m_{3/2}$. These apparently innocuous extra assumptions affect drastically the nature of the LSP, and the allowed regions of parameter space [9].

of the graviton, which would be a nightmare for astrophysical detection, but a potential bonanza for collider experiments. Here we concentrate on the neutralino option, whose classical signature is en event with missing transverse momentum carried away by invisible dark matter particles. This signature is shared by other WIMP candidates for dark matter, such as the LKP [2] and LTP [3], though the nature and kinematics of the visible stuff accompanying the dark matter particles is model-dependent.

3 Constraining Supersymmetry

There are significant lower limits on the possible masses of supersymmetric particles from LEP, which requires any charged sparticle to weigh more than about 100 GeV [13], and the Tevatron collider, which has not found any squarks or gluinos lighter than about 400 GeV [14]. There are also important indirect constraints implied by the LEP lower limit on the Higgs mass of 114.4 GeV [15], and the agreement of the Standard Model prediction for $b \rightarrow s\gamma$ decay with experimental measurements. The only possible experimental discrepancy with a Standard Model prediction is for $g_\mu - 2$ [16], though the significance of this discrepancy is still uncertain, as discussed in the following paragraph. However, there is one clear discrepancy with the Standard Model of particles, namely the density of dark matter, which cannot be explained without physics beyond the Standard Model, such as supersymmetry. The fact that the dark matter density is constrained to within a range of a few percent [17]:

$$\Omega_{DM} = 0.111 \pm 0.006 \tag{1}$$

constrains some combination of the parameters of any dark matter model also to within a few percent, as we shall see shortly in the case of supersymmetry, but the same would be true in other models.

The calculation of the Standard Model prediction for $g_\mu - 2$ requires an estimate of the contribution from hadronic vacuum polarization diagrams, that may be obtained either from $e^+e^- \rightarrow$ hadrons data, or from $\tau \rightarrow \nu+$ hadrons decays. Historically, there has been poor consistency between the e^+e^- and τ estimates (though both differ substantially from the experimental measurement), and the consistency between different e^+e^- experiments has not always been excellent. Since the τ estimate requires an isospin correction, the e^+e^- estimate is more direct and generally preferred. Accordingly, in the following results are shown assuming a discrepancy [18]

$$\Delta(g_\mu - 2) = (30.2 \pm 8.8) \times 10^{-10} \tag{2}$$

calculated from e^+e^- data to be explained by physics beyond the Standard Model, such as supersymmetry. Very recently, re-evaluations of the e^+e^- and τ data have yielded $\Delta(g_\mu - 2) = (28.7 \pm 8.0) \times 10^{-10}$ and $(19.5 \pm 8.3) \times 10^{-10}$ [19], corresponding to discrepancies of 3.6 and 2.4 σ, respectively. The results shown below would differ very little if the newer e^+e^- estimate were used. For comparison, some results from dropping the $g_\mu - 2$ constraint altogether are also shown, and using the τ decay estimate would give intermediate results closer to the e^+e^- estimate.

Fig. 1 demonstrates the impacts of the various theoretical, phenomenological, experimental and cosmological constraints in $(m_{1/2}, m_0)$ planes under different scenarios with $\mu > 0$, assuming that the LSP is the lightest neutralino, χ. The top panels are for the CMSSM with $A_0 = 0$ and (left) $\tan \beta = 10$, (right) $\tan \beta = 55$, two values that bracket the plausible range [20]. In both cases, we see narrow WMAP-compliant strips clinging near the boundaries of the (brown) charged LSP region at low m_0, where LSP-slepton coannihilation is important, and the (pink) region at high $m_{1/2}$ where electroweak symmetry is not broken consistently, called the focus-point strip. When $\tan \beta = 55$, we also see a diagonal funnel at large $m_{1/2}$ and m_0 due to rapid annihilation through direct-channel heavy Higgs poles. In the lower left panel, also for $\tan \beta = 10$, it is assumed that the scalar masses m_0 and the gaugino masses $m_{1/2}$ are universal at the scale 10^{17} GeV [11], instead of the GUT scale as in the CMSSM. We see that the coannihilation strip has shrunk into the region forbidden by the LEP Higgs limit, and the fixed-point strip has disappeared to larger m_0. On the other hand, if m_0 universality is assumed instead to hold at $10^{12.5}$ GeV, as in the bottom right panel, the coannihilation, fixed-point and funnel regions merge to form an atoll away from the boundaries of parameter space [10]. In what follows, the standard CMSSM and the NUHM1 model will be studied, but these panels emphasize that this involves a dicey assumption.

4   Global Supersymmetric Fits

Within the general CMSSM and NUHM frameworks, is it possible to find a preferred region of supersymmetric masses? To answer this question, we adopted a frequentist approach and constructed a global likelihood function using precision electroweak data, the LEP Higgs mass limit (allowing for theoretical uncertainties), the cold dark matter density, $b \to s\gamma$ and $B_s \to \mu^+\mu^-$ constraints and (optionally) $g_\mu - 2$ [21, 22, 23].

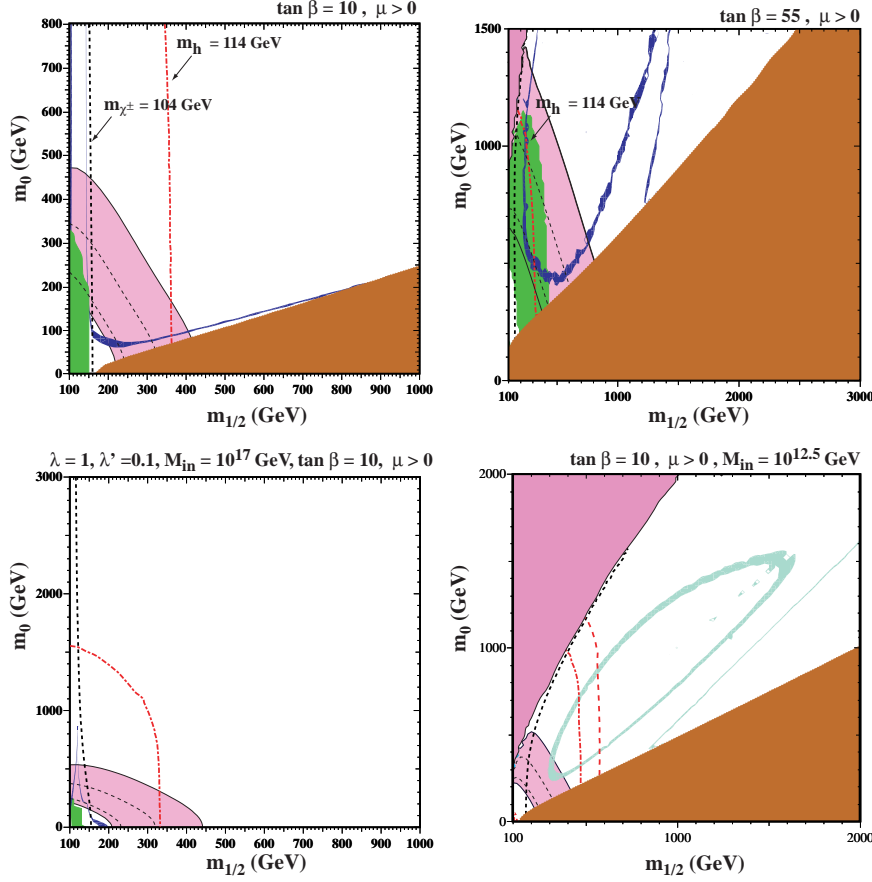In both the CMSSM and the NUHM1 we found that small $m_{1/2}$ and

Figure 1: *The $(m_{1/2}, m_0)$ planes for (upper left) the CMSSM with $\tan\beta = 10$ and (upper right) $\tan\beta = 55$ [20], (lower left) assuming SU(5) universality at 10^{17} GeV with representative choices of the quartic GUT Higgs couplings [11], and (lower right) assuming scalar mass universality at $10^{12.5}$ GeV [10], all assuming $\mu > 0, A_0 = 0, m_t = 173.1$ GeV and $m_b(m_b)_{SM}^{\overline{MS}} = 4.25$ GeV. The near-vertical (red) dot-dashed lines are the contours $m_h = 114$ GeV [15], and the near-vertical (black) dashed line is the contour $m_{\chi^\pm} = 104$ GeV [13]. The medium (dark green) shaded region is excluded by $b \to s\gamma$, and the dark (blue) shaded area is the cosmologically preferred region [17]. In the dark (brick red) shaded region, the LSP is the charged lighter stau slepton. The region allowed by the E821 measurement of $g_\mu - 2$ at the 2-σ level, is shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1-σ ranges.*

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m_0 in the coannihilation region are preferred, with the focus-point region disfavoured. The best-fit points, 68% and 95% CL regions in the $(m_0, m_{1/2})$ planes of the CMSSM and NUHM1 are shown in Fig. 2 [22], and the corresponding spectra are shown in Fig. 3 [23]. The favoured areas of the planes shown in Fig. 2 are quite sensitive to the treatments of the constraints, particularly $g_\mu - 2$ and $b \to s\gamma$ [22]. In the extreme case when the $g_\mu - 2$ constraint is dropped entirely, as in Fig. 4, large values of m_0 are no longer strongly disfavoured, although the other constraints still show some slight preference for small m_0 [23].
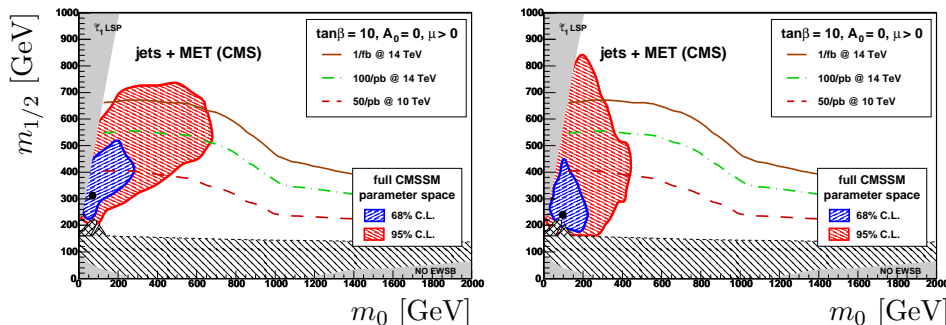

Figure 2: *The $(m_0, m_{1/2})$ planes for (left) the CMSSM and (right) the NUHM1. The dark shaded area at low m_0 and high $m_{1/2}$ is excluded due to a scalar tau LSP, and the light shaded areas at low $m_{1/2}$ do not exhibit electroweak symmetry breaking. The nearly horizontal line at $m_{1/2} \approx 160$ GeV in the lower panel has $m_{\tilde{\chi}_1^\pm} = 103$ GeV, and the area below is excluded by LEP searches. Just above this contour at low m_0 in the lower panel is the region that is excluded by trilepton searches at the Tevatron. Shown in each plot is the best-fit point, indicated by a filled circle, and the 68 (95)% C.L. contours from our fit as dark grey/blue (light grey/red) overlays [22]. Also shown are 5-σ discovery contours at the LHC with the indicated luminosities and centre-of-mass energies.*

Fig. 2 also shows the expected sensitivity of the LHC for a discovery of supersymmetry with 5-σ significance for varying LHC energies and luminosities. We see that there may be a fair chance to discover supersymmetry even in early LHC data. However, at the 95% CL, supersymmetry might still lie beyond the reach of the LHC with 1/fb of data at 14 TeV, as could also be inferred from the 95% CL ranges in Fig. 3.
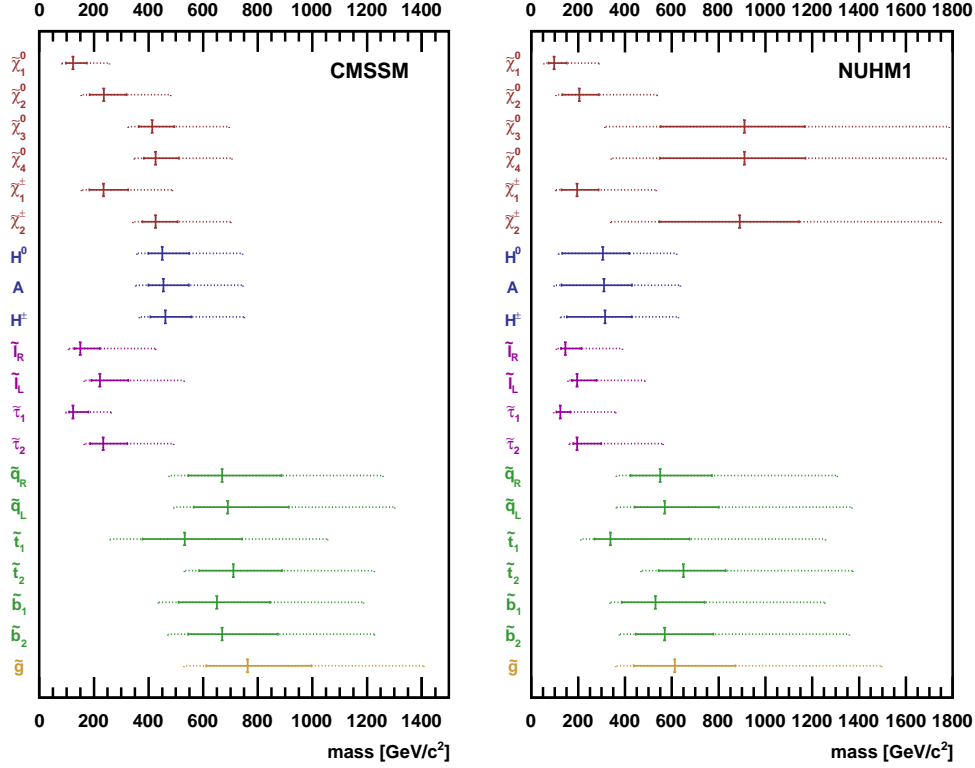
Figure 3: *Spectra in the CMSSM (left) and the NUHM1 (right). The vertical solid lines indicate the best-fit values, the horizontal solid lines are the 68% C.L. ranges, and the horizontal dashed lines are the 95% C.L. ranges for the indicated mass parameters [23].*

5   Detecting Supersymmetric Dark Matter

Several strategies for the detection of WIMP dark matter particles such as the LSP have been proposed, including the direct search for scattering on nuclei in the laboratory [24], the search for energetic neutrinos produced by WIMP annihilations in the core of the Sun or Earth [25], the search for energetic photons produced by WIMP annihilations in the galactic centre or elsewhere in the Universe [26], and the searches for positrons, antiprotons, etc., produced by WIMP annihilations in the galactic halo [27].

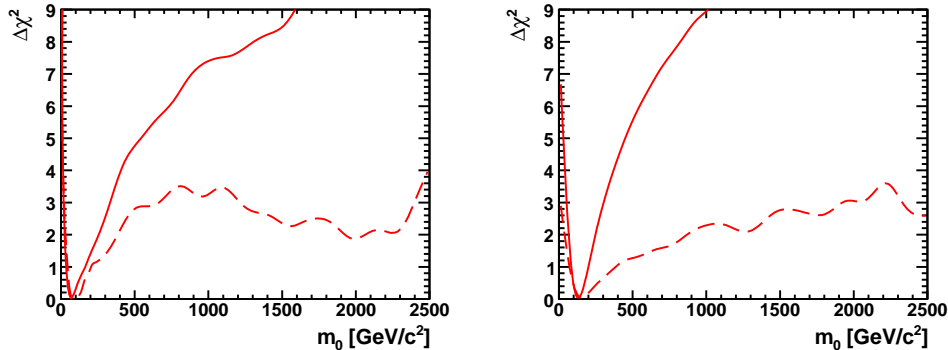As seen in Fig. 5, within the global fits to supersymmetric model pa-

Figure 4: *The likelihood functions for m_0 in the CMSSM (left plot) and in the NUHM1 (right plot). The χ^2 values are shown including (excluding) the $g_\mu - 2$ constraint as the solid (dashed) curves [23].*

rameters discussed earlier, our predictions for the direct nuclear scattering rates in the CMSSM and NUHM1 lie somewhat below the sensitivities of the CDMS and Xenon10 experiments, but within reach of planned upgrades of these experiments [23]. Subsequently, the CDMS II [28] and Xenon100 [29] experiments have announced results with somewhat improved sensitivity. In particular, the CDMS II experiment reported two events with relatively low recoil energies (corresponding possibly to the scattering of a WIMP weighing < 30 GeV) where less than one event was expected [28], but this hint was not confirmed by the Xenon100 experiment in its initial 11-day test run [29]. (Nor have possible signals in the DAMA/LIBRA [30] and CoGeNT experiments [31] been confirmed by either CDMS or Xenon100.) It is expected that updated Xenon100 results with much greater sensitivity will be announced soon, reaching significantly into the scattering rates expected within our global fits. (Though it should be noted that these predictions assume one particular value for the spin-independent scattering matrix element, which is a significant source of uncertainty in the predictions [32].)

The next most promising strategy for indirect detection of dark matter may be the search for energetic neutrinos emitted by WIMP annihilations in the core of the Sun [25]. It is often assumed that the annihilation rate is in equilibrium with the WIMP capture rate, but this is not true in general in the CMSSM [33]. Nor is spin-dependent scattering the dominant mechanism for LSP capture by the Sun, as is often assumed: spin-independent scattering on heavier elements inside the Sun may also be important, even
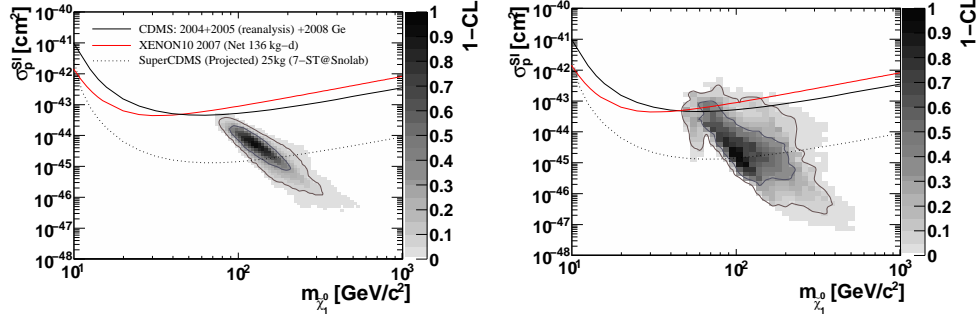
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Figure 5: *The correlation between the spin-independent dark matter scattering cross section and m_χ in the CMSSM (left panel) and in the NUHM1 (right panel). The solid lines [34] are the experimental upper limits from CDMS [35] and Xenon10[36], The dashed line [34] indicates the projected sensitivity of the SuperCDMS experiment [37]: that of Xenon100 may be similar.*

dominant [33]. As seen in Fig. 6, in a general survey of the CMSSM parameter space [33], we find significant portions of the focus-point strips, and some parts of the coannihilation strips, where the flux of energetic neutrinos due to LSP annihilations may be detectable in the IceCube/DeepCore experiment [38].

6 The Start-up of the LHC

The LHC made its first collisions on November 29th, 2009, and its first 7-TeV collisions on March 30th, 2010. Much jubilation, but where are the Higgs boson and supersymmetry, you may ask. It should be recalled that the total proton-proton cross section for producing a new particle weighing ~ 1 TeV is $\sim 1/\mathrm{TeV}^2$, possibly suppressed even further by small couplings $\sim \alpha^2$, whereas the total cross section $\sim 1/m_\pi^2$, so that the 'interesting' new physics signal is likely to occur in $\sim 10^{12}$ of the collisions. This is like looking for a needle in $\sim 100,000$ haystacks!

So far the LHC experiments have seen only a few $\times 10^{12}$ collisions. The missing E_T distribution agrees perfectly with simulations over more than 6 orders of magnitude [39], and there is no sign yet of an excess of events that might be due to the production and escape of dark matter particles, whether they be LSPs, LKPs, LTPs, or whatever. Moreover, the kinematics of the events with missing E_T is exactly what one would expect from mismeasured QCD events and other Standard Model backgrounds: no signs yet of new
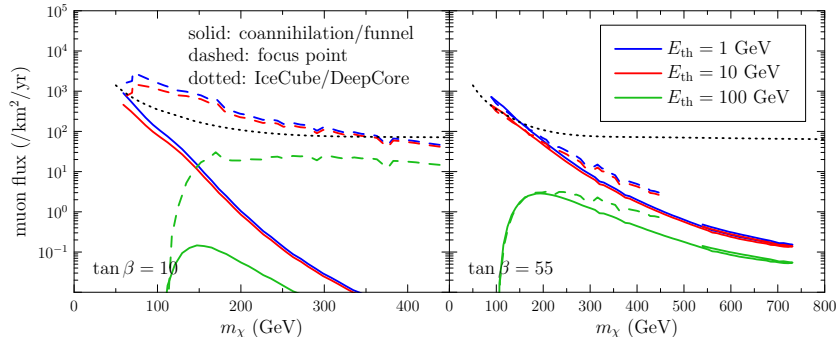
Figure 6: *The CMSSM muon fluxes though a detector calculated for $A_0 = 0$ and (left) $\tan\beta = 10$, (right) $\tan\beta = 55$, along the WMAP strips in the coannihilation/funnel regions (solid) and the focus-point region (dashed) [33]. Fluxes are shown for muon energy thresholds of (top to bottom) 1 GeV, 10 GeV, and 100 GeV. Also shown is a conservative estimate of the sensitivity of the IceCube/DeepCore detector (dotted) [38], normalized to a muon threshold of 1 GeV, for a particular hard annihilation spectrum that is a rough approximation to that expected in CMSSM models.*

physics beyond the Standard Model.

The results of our frequentist likelihood analysis were compared in Fig. 2 with the estimated sensitivity of the LHC at or close to its design energy. In 2010 it has been operating at ~ 7 TeV and accumulating ~ 50/pb of integrated luminosity, which is sufficient to extend the reach for supersymmetry beyond the Tevatron. The centre-of-mass energy may be increased in 2011 to 8 or 9 TeV, and the objective is to accumulate ~ 1/fb of integrated luminosity. Fig. 7 shows the estimated sensitivity of supersymmetry searches with the ATLAS experiment [40] using 1/fb of data at 7 TeV. Comparing with Fig. 2, we see that the best-fit points in the CMSSM and NUHM1 should lie within reach. There are significant prospects for soon getting some interesting news about supersymmetry, one way or the other.

7   A Conversation with Mrs. Thatcher

In 1982, Mrs. Thatcher, the British Prime Minister at the time, visited CERN, and I was introduced to her as a theoretical physicist. "What exactly do you do?", she asked in her inimitably intimidating manner. "I think of things for experimentalists to look for, and then I hope they find some-
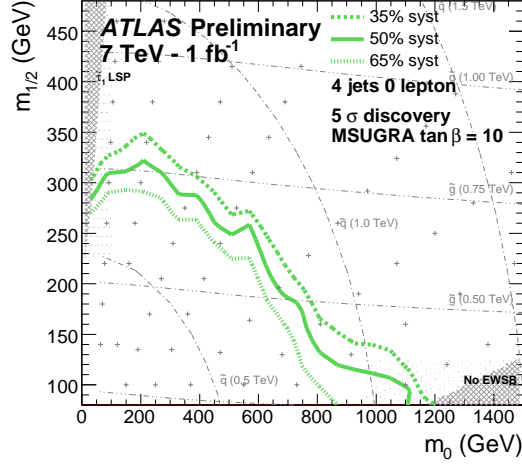
Figure 7: *The sensitivity in the $(m_0, m_{1/2})$ plane of the ATLAS experiment for a 5-σ discovery of a supersymmetric signal with 1/fb at 7 TeV in the centre of mass.*

thing different", I responded. Somewhat predictably, Mrs. Thatcher asked "Wouldn't it be better if they found what you predicted?" My response was that "If they found exactly what the theorists predicted, we would not be learning so much". In much the same spirit, I hope (and indeed expect) that the LHC will become most famous for discovering something that I did NOT discuss in this talk - as long as it casts light on dark matter!

References

[1] M. Bustamante, L. Cieri and J. Ellis, arXiv:0911.4409 [hep-ph]; in *Proceedings of the 2009 CERN-Latin-American School of High-Energy Physics, Recinto Quirama, Colombia, 15 - 28 March 2009*, eds. C. Grojean and M. Spiropulu, arXiv:1010.5976 [hep-ph].

[2] G. Servant and T. M. P. Tait, Nucl. Phys. B **650** (2003) 391 [arXiv:hep-ph/0206071].

[3] H. C. Cheng and I. Low, **JHEP** 0309 (2003) 051 and **JHEP** 0408 (2004) 061.

[4] J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, Nucl. Phys. B **238** (1984) 453; see also H. Goldberg, Phys. Rev. Lett. **50** (1983) 1419.

[5] L. Maiani, *All You Need To Know About The Higgs Boson*, Proceedings of the Gif-sur-Yvette Summer School On Particle Physics, 1979, pp.1-52; G. 't Hooft, in *Recent developments in Gauge Theories*, Proceedings of the NATO Advanced Study Institute, Cargèse, 1979, eds. G. 't Hooft et al. (Plenum Press, NY, 1980); E. Witten, Phys. Lett. B **105** (1981) 267.

[6] ALEPH, CDF, D0, DELPHI, L3, OPAL and SLD Collaborations, LEP and Tevatron Electroweak Working Groups, SLD Electroweak and Heavy Flavour Groups, arXiv:0911.2604.

[7] J. Ellis, S. Kelley and D.V. Nanopoulos, Phys. Lett. **260** (1991) 131; U. Amaldi, W. de Boer and H. Furstenau, Phys. Lett. **B260** (1991) 447; P. Langacker and M. Luo, Phys. Rev. **D44** (1991) 817; C. Giunti, C. W. Kim and U. W. Lee, Mod. Phys. Lett. A **6** (1991) 1745.

[8] H. P. Nilles, Phys. Rept. **110**, 1 (1984); H. E. Haber and G. L. Kane, Phys. Rept. **117**, 75 (1985). S. P. Martin, *A Supersymmetry Primer*, arXiv:hep-ph/9709356.

[9] J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Rev. D **70**, 055005 (2004) [arXiv:hep-ph/0405110].

[10] J. R. Ellis, K. A. Olive and P. Sandick, Phys. Lett. B **642**, 389 (2006) [arXiv:hep-ph/0607002];

[11] J. Ellis, A. Mustafayev and K. A. Olive, Eur. Phys. J. C **69** (2010) 201 [arXiv:1003.3677 [hep-ph]].

[12] J. R. Ellis and D. V. Nanopoulos, Phys. Lett. B **110** (1982) 44.

[13] Joint Supersymmetry Working Group of the ALEPH, DELPHI, L3 and OPAL experiments, `http://lepsusy.web.cern.ch/lepsusy/`.

[14] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).

[15] S. Schael *et al.* [ALEPH, DELPHI, L3, OPAL Collaborations and LEP Working Group for Higgs boson searches], Eur. Phys. J. C **47** (2006) 547 [arXiv:hep-ex/0602042].

[16] G. W. Bennett *et al.* [Muon g-2 Collaboration], Phys. Rev. Lett. **92** (2004) 161802 [arXiv:hep-ex/0401008].

[17] E. Komatsu *et al.*, arXiv:1001.4538 [astro-ph.CO] and references therein.

[18] M. Davier, A. Hoecker, B. Malaescu, C. Z. Yuan and Z. Zhang, arXiv:0908.4300 [hep-ph].

[19] M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, arXiv:1010.4180 [hep-ph].

[20] J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Lett. B **565**, 176 (2003) [arXiv:hep-ph/0303043].

[21] O. Buchmueller *et al.*, Phys. Lett. B **657** (2007) 87 [arXiv:0707.3447 [hep-ph]].

[22] O. Buchmueller *et al.*, JHEP **0809** (2008) 117 [arXiv:0808.4128 [hep-ph]].

[23] O. Buchmueller *et al.*, Eur. Phys. J. C **64** (2009) 391 [arXiv:0907.5568 [hep-ph]].

[24] M. W. Goodman and E. Witten, Phys. Rev. D **31** (1985) 3059.

[25] M. Srednicki, K. A. Olive and J. Silk, Nucl. Phys. B **279** (1987) 804.

[26] See, for example, P. Scott, J. Conrad, J. Edsjo, L. Bergstrom, C. Farnier and Y. Akrami, JCAP **1001** (2010) 031 [arXiv:0909.3300 [astro-ph.CO]] and references therein.

[27] J. Silk and M. Srednicki, Phys. Rev. Lett. **53** (1984) 624.

[28] Z. Ahmed *et al.* [The CDMS-II Collaboration], Science **327** (2010) 1619 [arXiv:0912.3592 [astro-ph.CO]].

[29] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **105** (2010) 131302 [arXiv:1005.0380 [astro-ph.CO]].

[30] R. Bernabei *et al.*, arXiv:1007.0595 [astro-ph.CO].

[31] C. E. Aalseth *et al.* [CoGeNT collaboration], arXiv:1002.4703 [astro-ph.CO].

[32] J. R. Ellis, K. A. Olive and C. Savage, Phys. Rev. D **77** (2008) 065026 [arXiv:0801.3656 [hep-ph]].

[33] J. Ellis, K. A. Olive, C. Savage and V. C. Spanos, Phys. Rev. D **81** (2010) 085004 [arXiv:0912.3137 [hep-ph]].

[34] R. Gaitskell and J. Filippini, `http://dmtools.berkeley.edu/ slimitplots/` .

[35] Z. Ahmed *et al.* [CDMS Collaboration], Phys. Rev. Lett. **102** (2009) 011301 [arXiv:0802.3530 [astro-ph]].

[36] J. Angle *et al.*, Phys. Rev. Lett. **101** (2008) 091301 [arXiv:0805.2939 [astro-ph]].

[37] SuperCDMS Development Project, Fermilab Proposal 0947, October 2004.

[38] J. Ahrens *et al.* [IceCube Collaboration], Astropart. Phys. **20**, 507 (2004) [arXiv:astro-ph/0305196].

[39] See, for example T. Le Compte, Talk at the 103rd Open Session of the LHCC, `http://indico.cern.ch/getFile.py/access?contribId=2 &resId=1&materialId=slides&confId=105780`.

[40] ATLAS Collaboration, `http://cdsweb.cern.ch/record/1278474/ files/ATL-PHYS-PUB-2010-010.pdf`; see also
CMS Collaboration, CMS-NOTE-2010-008, `https://twiki.cern.ch/ twiki/bin/view/CMSPublic/PhysicsResultsSUS`.